Are extrasolar oceans common throughout the Galaxy?

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Light and cold extrasolar planets such as OGLE 2005-BLG-390Lb, a 5.5 Earth-mass planet detected via microlensing, could be frequent in the Galaxy according to some preliminary results from microlensing experiments. These planets can be frozen rocky- or ocean-planets, situated beyond the snow line and, therefore, beyond the habitable zone of their system. They can nonetheless host a layer of liquid water, heated by radiogenic energy, underneath an ice shell surface for billions of years, before freezing completely. These results suggest that oceans under ice, like those suspected to be present on icy moons in the Solar system, could be a common feature of cold low-mass extrasolar planets.

1 Introduction

More than 200 extrasolar planets have been detected during the past 15 years. Aside from the planetary search by itself, the refinement and multiplication of detection techniques have allowed to determine several physical properties of the targeted planets, including their mean density, hence their nature. Roughly 90% of the detected planets[1] have masses within two orders of magnitude of Jupiter's mass (M_{J}); they are thought to be gaseous giants. Combined planetary mass and radius measurements have confirmed this fact for nearly all planets transiting their stars, for which a radius measurement is possible.

Transiting planets less massive than 'hot Jupiters' will hopefully be found by transit search missions *CoRoT* (flying) and *Kepler* (launch scheduled for 2008). Meanwhile, it is rather difficult to infer the natures, either gaseous, icy, or rocky, of Uranus- and lower-mass planets ($\lesssim 15$ Earth masses, $M_{\oplus}$). In fact, the 'critical' core mass usually considered to separate the formation processes of telluric and giant planets in the Solar system is ~ 8 $M_{\oplus}$ (Wuchterl et al. 2000). This theoretical limit, however, should not be applied *as it is* to extrasolar planets, as illustrated by the ambiguous case of HD 149026b, a $\sim M_{\mathrm{J}}$ planet suspected to host a massive dense core in order to explain its small radius (Sato et al. 2005; Fortney et al. 2006; Broeg & Wuchterl 2007).

Foreseeing the possible diversity of low-mass planets, models of different internal structures and atmospheres have been recently flourishing. These speculative descriptions ba-

sically distinguish between Earth-like rocky planets (Valencia et al. 2006, 2007; Sotin et al. 2007) and more water-rich planets, hypothetical 'ocean-planets' (Kuchner 2003; Léger et al. 2004; Sotin et al. 2007; Selsis et al. 2007). The detections of planets GJ 876d (7.5 $M_{\oplus}$, Rivera et al. 2005) by radial velocimetry and OGLE 2005-BLG-390Lb (5.5 $M_{\oplus}$, Beaulieu et al. 2006) by microlensing justify these modeling approaches and allow the first model applications.

Ehrenreich et al. (2006; hereafter, E06) have used observational constrains from Beaulieu et al. (2006) together with modeling from Sotin et al. (2007) and Hussmann et al. (2002) to characterize OGLE 2005-BLG-390Lb. They raised the possibility that this cold (~ 40 K) low-mass planet could host a liquid water ocean under an ice shell surface, similarly to some icy moons in the Solar System, according to current models (see, e.g., Spohn & Schubert 2003; Hussmann et al. 2006).

In this speculative paper, we combine the first results on microlensing searches detection efficiency and the results of E06, to highlight the fact that planets similar to OGLE 2005-BLG-390Lb could be more abundant than gaseous giants—and potentially common throughout the Galaxy. This would make them particularly interesting objects to study, especially if the conditions allowing for the existence of oceans are fulfilled.

2 Microlensing detection efficiency

Current ground-based microlensing searches probe distant (at several kpc) cool planetary companions in the range 1–10 astronomical units (AU), preferentially around M- and K-dwarf hosts, with masses down to a few Earths. The PLANET/Robonet

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[1] See the *Extrasolar planets encyclopaedia* (http://exoplanet.eu).

(Probing Lensing Anomalies NETwork) collaboration operates a round-the-clock follow-up on ongoing microlensing events towards the Galactic bulge, by means of currently eight 1–2m-class telescopes situated in the south hemisphere.

Some promising detections have recently been made, with the discoveries of two gas giants of a few Jupiter masses, MOA 2003-BLG-53Lb (Bond et al. 2004) and OGLE 2005-BLG-071Lb (Udalski et al. 2005), a Neptune-mass planet OGLE 2005-BLG-169Lb (Gould et al. 2006) and the rocky/icy planet OGLE 2005-BLG-390Lb (Beaulieu et al. 2006).

Kubas et al. (2007, submitted) have computed the detection probability for OGLE 2005-BLG-390Lb-like planets, and find that, assuming a perfect observational setup, it does not exceed 3%. Furthermore, they also compute the probability of detecting an additional Jupiter-mass planet to the system, and find it is greater than 50% for orbits between 1.1 and 2.3 AU. Therefore, OGLE 2005-BLG-390Lb was detected in spite of a low detection probability, while no giant companion was found, even with a rather high detection efficiency. This fact supports the core accretion theory which predicts that sub-Neptune mass planets are more common than giants around M dwarfs, as also pointed out by Gould et al. (2006).

One can go further in the conclusion by computing the detection efficiency of the microlensing searches. This is done by determining for many microlensing events which do not show obvious planetary signature, to which extent the data rule out the presence of a planetary companion to the lens. While a detailed and complete analysis including 11 years of PLANET observations (1995–2005) will be provided by Cassan et al. (2007, in prep.), a preliminary result can be derived from the 2004 season (Cassan & Kubas 2007).

Figure 1 presents the mean detection efficiency iso-contours (in percent) as a function of planet mass and separation, combining 14 well sampled events from the 2004 PLANET season alone. This diagram is produced by computing for every individual event their detection efficiency as a function of the planet-to-star mass ratio and the instantaneous separation, and use an appropriate Galactic model with a Bayesian analysis (Dominik 2006) to convert the parameters in physical units of the planet properties (mass and separation in AU). The detected planets are over-plotted on the same figure, which allows to give preliminary qualitative conclusion.

Hence, combining detections and detection efficiency, one can evaluate which kind of planets can be 'easily' found but are actually not, and those which were detected despite a small probability. It appears that in spite of the difference in detection efficiencies for $\sim 1\ M_J$ and 1–15 $M_\oplus$ planets, the same number of objects has been evidenced in each category. This suggests that 1–15 $M_\oplus$ planets are more common around low-mass stars than giant gaseous planets.

Of course, we shall temper this affirmation given the small number of detections so far; however, it is in accordance with the core-accretion theory of planet formation
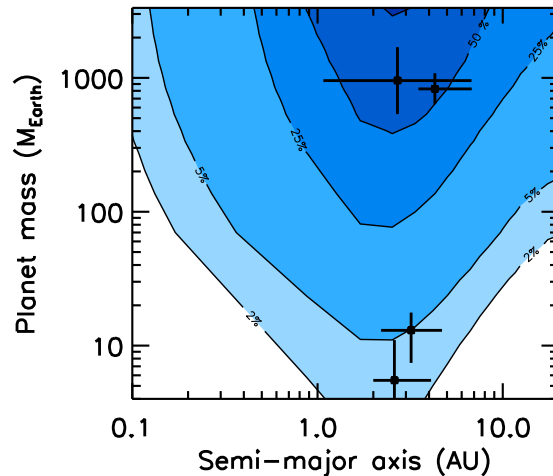
Fig. 1   Average detection efficiency of planets as a function of mass and orbital separation (assuming circular orbits) in the 14 favourable events monitored by PLANET in 2004 (preliminary analysis) along with the planets detected by microlensing as of 2006 marked as dots. For Jupiter-mass planets, the detection efficiency reaches 50%, while it decreases only with the square-root of the planet mass until the detection of planets is further suppressed by the finite size of the source stars for planets with a few Earth masses. Nevertheless, the detection efficiency still remains a few per cent for rocky/icy planets below 10 Earth masses.

around low-mass stars (Laughlin et al. 2004). Since those stars represent the major fraction of the stars in the Galactic disk (Chabrier 2001), the observations of Gould et al. (2006) and Beaulieu et al. (2006) implies that low-mass planets are frequent in the Milky Way.

3   Oceans in frozen low-mass planets

According to Beaulieu et al. (2006) calculated uncertainties, OGLE 2005-BLG-390Lb has a mass between 3 and 11 $M_\oplus$ and a semi-major axis between 2 and 4 AU. The mass of the parent star is between 0.1 and 0.4 solar mass ($M_\odot$). It is potentially the lightest extrasolar planet detected so far, and according to the previous section and the rather large errorbars associated with its mass and semi-major axis, this planet could be representative of a large fraction of planets around M dwarfs. Such stars would provide very few energy per surface unit to the distant planet (2–4 AU), typically that of Pluto in the Solar system ($\sim 0.1\ W\,m^{-2}$). Hence, the planet can be either a cold and massive analog of the Earth, or a frozen ocean-planet (Léger et al. 2004). In both cases, it could have a solid icy surface with temperatures of ~ 40 K. In spite of that, E06 showed that it could host a subsurface liquid water ocean under the ice shell surface, depending on the ice-to-rock mass ratio and age of the planet/star.

3.1   The ice-to-rock mass ratio

The total mass of ice in the planet relatively to the quantity of refractory elements (metals and rocks), the ice-to-rock mass ratio (I/R), is treated as a free parameter in E06. They used the mass-radius relation from Sotin et al. (2007) to determine the planetary radius for different I/R, namely $\sim 10^{-4}$, 0.33, and 1. Since ice is less dense than rock, a planet containing more ice is also larger than a same-mass rocky planet.

The first case, $I/R \sim 10^{-4}$, in fact applies to a rocky planet with a H_2O content similar to the Earth one; there, an ice layer covering the rocky mantle would be rather thin ($\lesssim 10$ km) compared to the planetary radius, and composed exclusively of low-pressure ice. In the last two cases, $I/R \sim 0.33$ and $I/R \sim 1$, the planet could be a massive intermediate between Europa and Ganymede, and a hypothetical ocean-planet, respectively. There, a non-negligible fraction of the planetary mass is accounted for by water, and the thick ice shell must be largely composed of high-pressure ice due to the strong gravity. However, E06 distinguish between a thin ($\lesssim 60$ km) low-pressure ice overtopping a thick ($\sim 1\,000$ km) high-pressure icy mantle. The negative slope of the low-pressure H_2O ice melting curve as a function of pressure makes the existence of a $\lesssim 50$-km-thick ocean possible at the bottom of the low-pressure ice layer. The different possibilities are sketched in Fig. 2.

3.2   Heating *versus* cooling of the subsurface ocean

Knowing that the age of the planet and star is ~ 10 Gyr, a typical age for a star of the Bulge, and given the negligible irradiation the planet is receiving at its surface (~ 0.1 W m^{-2}), the existence of liquid water requires an internal heat source capable of melting the ice in the depths. This source could be the decay of radioactive long-lived isotopes of uranium, thorium, and potassium, possibly included in the rocky mantle. The internal heat production per unit of mass is $h = f \sum_i h_i X_i(t)$, where h_i is the heat produced by the isotope i per unit of mass, $X_i(t)$ is the mass fraction of this isotope at a time t, and f is the mass fraction of rocks in the planet. The more rocks within the planet—i.e., the lower the I/R ratio—and the younger it is, the larger the heat production.

To have a liquid layer below the ice shell, the temperature must reach at least ~ 250 K above the point where the slope of the melting curve becomes positive with pressure/depth. This point is situated at a pressure of ~ 0.2 GPa, which corresponds to a depth < 100 km for the range of planetary masses and radii considered here. In other words, the top of the ocean cannot be deeper than 100 km beneath the surface.

This thin ice shell surface, relatively to the size of the planet, can be even thinner depending on the total quantity of ice in the planet. For $I/R \sim 10^{-4}$, the ice shell cannot be thicker than ~ 10 km. In this case, E06 showed that the heat loss is too fast to allow the survival of a subsurface ocean after 10 Gyr—the age supposed for OGLE 2005-BLG-390Lb—despite a large heat production rate. The maximum 100-km thickness ice shell better isolating the liquid layer from the cold surface is reached in models with $I/R \sim 1$ (ocean-planets). However, as we seen above, the heat production is too low to make the temperature reach the critical 250 K at this depth.

In fact, a 'compromise' value could be found around $I/R \sim 0.33$, in order to have both a sufficient heat production rate and a sufficiently thick ice shell surface. Therefore, icy planets with a composition between that of Europa ($I/R \sim 0.1$) and Ganymede ($I/R \sim 0.5$), may be better place to find an ocean under an ice shell.

In any cases, E06 concluded that owing to its age (~ 10 Gyr), OGLE 2005-BLG-390Lb is most likely entirely frozen (Figs. 2*b* or 2*d*). It is however possible to roughly estimate since how long the ocean is condensed. The present value of the heat production should be increased by a factor 2.1 to 2.5 in order to have liquid water in the 10-Gyr-old planet, assuming $I/R \sim 0.33$. These values of the heat production rate were in fact reached when the planet was ~ 4-Gyr old.

This estimation assumes that radiogenic heating is the only heat source in the planet interior. However, it should be regarded as a minimum value since it does not consider the remnant heat from the accretion, which is certainly not negligible, in particular for such a massive planet. This allows to suggest that liquid water was certainly present in the past during several billion years below the surface of OGLE 2005-BLG-390Lb, and might be commonly found on similar but younger planets.

4   Conclusions

First results from microlensing surveys suggest that planets less massive than Uranus or Neptune are more common around low-mass stars than giant gaseous planets, as proposed by the core-accretion theory. Low-mass stars, in turn, are the most represented stellar population in the Galaxy. It is therefore relevant to study what kind of planets they could host. They could be similar to OGLE 2005-BLG-390Lb, a few times more massive than Earth and completely frozen, unless they are composed by about 3/4 of rocks and metals and 1/4 of ice, in mass. This 'recipe' indeed favors the presence of a liquid layer beneath a frozen surface. It is close to the composition of icy satellites in the Solar system, such as Europa or Ganymede. These objects have long been suspected of hosting liquid water—a suspicion that has now spread onto less massive satellites and Kuiper belt objects (Hussmann et al. 2006), and on low-mass extrasolar planets (Léger et al. 2004; E06).

It implies that 'oceans under ice' could be a common feature of low-mass extrasolar planets, largely spread around low-mass stars in the Galaxy. This is an interesting perspective for astrobiology, because oceans, even under an ice
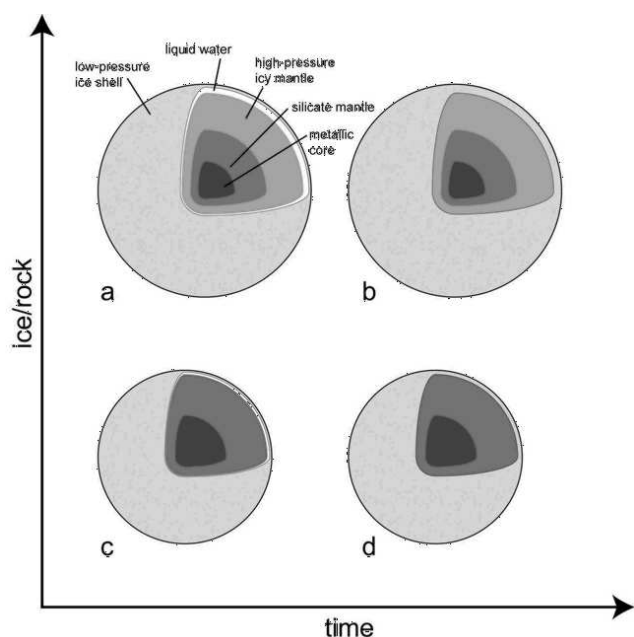
Fig. 2 Sketches of the possible internal structures of OGLE 2005-BLG-390Lb and analog planets in the same range of mass/semi-major axis. Panel a shows a young planet with I/R typically ~ 1, where an ocean (*white*) is found beneath a thin ice shell surface. The planet is composed by a metallic core, rocky mantle, and high-pressure icy mantle (*from darker to lighter grey*). Panel b shows the same planet at a more advanced age, where the radioactive heating has decreased and the ocean has condensed. The same evolution is figured for a rocky planet ($I/R \sim 10^{-4}$) in panels c and d. In this case, the planet is mostly composed by a metallic core and a rocky mantle, overtopped by a tenuous ice shell. See E06 and Sotin et al. (2007) for details.

shell, are *a priori* good places for the apparition/subsistence of life.

In return, this underlines the needs and highlights the interests for studying Solar system frozen bodies, such as icy moons and Kuiper belt objects, especially through space exploration missions capable of *in situ* probing of the oceans potentially present there. These oceans might be common throughout the Galaxy.

References

Beaulieu, J.-P., Bennett, D.P., Fouqué, P., et al.: 2006, Nature 439, 437

Bond, I.A., Udalski, A., Jaroszyński, M., et al.: 2004, ApJ 606, L155

Broeg, C., Wuchterl, G.: 2007, MNRAS , in press (astro-ph/0701340)

Cassan, A., Kubas, D.: 2007, ASP, in press (astro-ph/0612014)

Cassan, A., Kubas, D., Dominik, M., et al.: 2007, in preparation

Chabrier, G.: 2001, ApJ 554, 1274

Dominik, M.: 2006, MNRAS 367, 669

Ehrenreich, D., Lecavelier des Etangs, A., Beaulieu, J.-P., Grasset, O.: 2006, ApJ 651, 535

Fortney, J.J., Saumon, D., Marley, M.S., Lodders, K., Freedman, R.S.: 2006, ApJ 642, 495

Gould, A., Udalski, A., An, D., et al.: 2006, ApJ 644, L37

Hussmann, H., Spohn, T., Wierczerkowski, K.: 2002, Icarus 156, 143

Hussmann, H., Sohl, F., Spohn, T.: 2006, Icarus 185, 258

Kubas, D., Cassan, A., Dominik, M., et al.: 2007, submitted.

Kuchner, M.: 2003, ApJ 596, L105

Laughlin, G., Bodenheimer, P., Adams, F.C.: 2004, ApJ 612, L73

Léger, A., Selsis, F., Sotin, C., et al.: 2004, Icarus 169, 499

Rivera, E.J., Lissauer, J.J., Butler, R.P., et al.: 2005, ApJ 634, 625

Sato, B., Fischer, D., Henry, G.W., et al.: 2005, ApJ 633, 465

Selsis, F., Chazelas, B., Bordé, P., et al.: 2007, submitted to Icarus

Sotin, C., Grasset, O., Moquet, A.: 2007, Icarus, in press

Schneider, J., Dedieu, C.: 2007. The extrasolar planets encyclopaedia (http://exoplanet.eu)

Spohn, T., Schubert, G.: 2003, Icarus 161, 456

Udalski, A., Jaroszyński, M., Paczyński, B., et al.: 2005, ApJ 628, L109

Valencia, D., O'Connell, R.J., Sasselov, D.D.: 2006, Icarus 181, 545

Valencia, D., Sasselov, D.D., O'Connell, R.J.: 2007, ApJ 656, 545

Wuchterl, G., Guillot, T., & Lissauer, J.J.: 2000. Giant planet formation. In: Protostars and planets vol. IV, ed. V. Mannings, A.P. Boss, S.S. Russell (Tucson: Univ. of Arizona Press), 1081